Massive molecular outflows at high spatial resolution

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ABSTRACT

We present high-spatial resolution Plateau de Bure Interferometer CO(2–1) and SiO(2–1) observations of one intermediate-mass and one high-mass star-forming region. The intermediate-mass region IRAS 20293+3952 exhibits four molecular outflows, one being as collimated as the highly collimated jet-like outflows observed in low-mass star formation sources. Furthermore, comparing the data with additional infrared H_2 and cm observations we see indications that the nearby ultracompact HII region triggers a shock wave interacting with the outflow. The high-mass region IRAS 19217+1651 exhibits a bipolar outflow as well and the region is dominated by the central driving source. Adding two more sources from the literature, we compare position-velocity diagrams of the intermediate- to high-mass sources with previous studies in the low-mass regime. We find similar kinematic signatures, some sources can be explained by jet-driven outflows whereas other are better constrained by wind-driven models. The data also allow to estimate accretion rates varying from a few times $10^{-5}\,\mathrm{M_\odot yr^{-1}}$ for the intermediate-mass sources to a few times $10^{-4}\,\mathrm{M_\odot yr^{-1}}$ for the high-mass source, consistent with models explaining star formation of all masses via accretion processes.

Subject headings: accretion, accretion disks – techniques: interferometric – stars: formation – ISM: jets and outflows – ISM: individual (IRAS 19217+1651; IRAS 20293+3952)

1. Introduction

Studies of massive molecular outflows have revealed many important insights in the formation of massive stars over recent years. Based on the morphologies and energetics we can deduce physical processes taking place at the inner center of the regions. Several single-dish studies agree on the results that massive molecular outflows are ubiquitous phenomena in massive star formation and that they are far more massive and energetic than their low-mass counterparts (e.g., Shepherd & Churchwell 1996b; Ridge & Moore 2001; Zhang et al. 2001; Beuther et al. 2002c).

A point these studies disagree on is the degree of collimation of massive outflows. Based on early studies by Shepherd & Churchwell (1996a) and its follow-ups, it was believed that high-mass outflows tend to be less collimated than low-mass flows. As the outflow collimation is theoretically tightly connected with the accretion process, these studies favored the idea that massive stars might form via different physical processes, e.g., the coalescence of intermediate-mass protostars at the very center of dense evolving cluster (Bonnell et al. 1998; Stahler et al. 2000; Bally 2002).

However, recent observations by Beuther et al. (2002c) show that the previously claimed lower collimation of massive outflows is mostly an observational artifact caused by the larger distances of the target sources (on the average a few kpc) and too low spatial resolution of most studies. Their data taken with the IRAM 30 m telescope at a spatial resolution of 11″ are consistent with massive, bipolar outflows as collimated as their low-mass counterparts. This implies that massive stars can form in a qualitatively similar manner as low-mass stars, just with accretion rates increased by orders of magnitude.

These latter observations are still based on single-dish observations, and to substantiate the scenario a statistically significant number of high-spatial-resolution interferometer studies of massive molecular outflows is necessary. As a first step in that direction Beuther et al. (2002a) have observed the massive star-forming region IRAS 05358+3543 with the Plateau de Bure Interferometer (PdBI) in CO(1–0), SiO(2–1) and $H^{13}CO^+$(1–0). They observed a massive outflow from the central object of the evolving cluster which is jet-like and highly collimated with a collimation degree of 10. This is the upper end of collimation degrees observed for low-mass outflows as well (Richer et al. 2000). In addition to that collimated jet-like structure, they observed at least two more outflows within the same region. In another source, IRAS 19410+2336, the two outflows observed at single-dish resolution split up at least into 7 separate outflows when observed with interferometers (Beuther et al. 2003). Similar results were observed toward G35.2 by Gibb et al. (2003). One of the main conclusions of these studies is that massive star-forming regions can appear confusing with single-dish instruments, but that it is possible to disentangle the structures with high enough

spatial resolution into features well known from low-mass star formation.

Contrary, other high-spatial-resolution studies of high-mass star-forming regions indicate that massive outflows can also appear morphologically and energetically different to their low-mass counterparts (e.g., Shepherd et al. 1998, 2003). As the high-spatial-resolution results are still based on poor statistical grounds, we pursued massive outflow studies with the PdBI[1]. Here we present the results of two more regions – IRAS 19217+1651 and IRAS 20293+3952 – observed at an angular resolution as high as 1.8″ in CO(2–1) and SiO(2–1). The two sources are part of a large and well studied sample of 69 high-mass protostellar objects at early evolutionary stages prior to producing significant ultracompact Hii (UCHii) regions (Sridharan et al. 2002; Beuther et al. 2002b,c,d). The two sources were chosen because they combine different features of massive star formation: IRAS 19217+1651 has a luminosity of $10^{4.9}\,L_\odot$ and shows a rather simple morphology with one mm continuum source associated with cm emission and H_2O and class II CH_3OH masers. Contrary, IRAS 20293+3952 contains a small UCHii region, contributing most of the bolometric luminosity ($10^{3.8}\,L_\odot$, Sridharan et al. 2002), and likely a cluster of younger intermediate-mass sources triggering the molecular outflows. While the single-dish outflow map of IRAS 19217+1651 shows a well-defined bipolar morphology, already the single-dish data of IRAS 20293+3952 show that we are dealing with multiple outflows in that region (Beuther et al. 2002c). Both sources cover a wide range of characteristics from intermediate- to high-mass star formation, the main source parameters are listed in Table 1.

After describing the observations in §2, we present the observational results for both sources separately in §3. Then we discuss the results in the framework of massive star formation and include literature data with special regard to the position-velocity structure of massive outflows in §4. Finally, §5 draws the conclusions, summarizes the current stage of massive molecular outflow studies, and outlines main topics to be tackled in the coming years.

2. Observations

2.1. Plateau de Bure Interferometer (PdBI)

We observed IRAS 19217+1632 and IRAS 20293+3952 in different runs from November 1999 to February 2002 with the Plateau de Bure Interferometer at 1.3 mm and at 3 mm in the C and D configurations with 4 antennas in 1999 and 5 antennas in 2002. The 1 mm

[1]IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).

receivers were tuned to the CO(2–1) line at 230.5 GHz, and the 3 mm receivers covered the SiO(2–1) line at 86.85 GHz.

The typical system temperatures at 1.3 mm are about 300 K and at 3 mm about 135 K. The phase noise was mostly below 20° and always below 30°. After smoothing the data, the final velocity resolution in both lines is $1\,\mathrm{km\,s^{-1}}$, adequate to sample the broad wing emission of the outflows. Atmospheric phase correction based on the 1.3 mm total power was applied. For continuum measurements, we placed two 320 MHz correlator units in each band to cover the largest possible bandwidths. The primary beam at 1.3 mm is $22''$, and to cover both regions completely mosaics were necessary. In IRAS 19217+1651 the mosaic consisted of 5 fields (offsets [$''$]: 19/33, 12/24, 6/14, 0/4, -5/-6) and in IRAS 20293+3952 of 8 fields (offsets [$''$]: 24/10, 12/7, 2/4, -10/1, 36/15, 32/3, 32/-9 32/-20) with respect to the phase reference centers listed in Table 1. The somewhat peculiar V-shaped mosaic for IRAS 20293+3952 was chosen based on the previous single-dish observations (Beuther et al. 2002c). Temporal fluctuations of the amplitude and phase were calibrated with frequent observations of the quasars 1923+210, 2032+107 and 2013+370. The amplitude scale was derived from measurements of MWC349 and 3C345, and we estimate the final flux density accuracy to be $\sim 15\%$. Synthesized beams at the different wavelengths are listed in Table 2.

2.2. Short spacings with the IRAM 30 m telescope

To account for the missing short spacings and to recover the line-flux, we also observed the source in CO(2–1) at $11''$ resolution with the IRAM 30 m telescope in Summer 2002. The observations were done remotely from the Max-Planck-Institut für Radioastronomie (MPIfR) Bonn in the on-the-fly mode. Typical system temperatures at 1.3 mm were around 400 K, the data were sampled in $4''$ increments (Nyquist sampling is $\frac{\lambda}{2D} \sim 4.5''$) and the velocity resolution was $0.1\,\mathrm{km\,s^{-1}}$.

The algorithm to derive visibilities from the single-dish data corresponding to each pointing center is described by Gueth et al. (1996). The single-dish and interferometer visibilities are subsequently processed together. Relative weighting has been chosen to minimize the negative side-lobes in the resulting dirty beam while keeping the highest angular resolution possible. Images were produced using natural weighting, then a CLEAN-based deconvolution of the mosaic was performed. Synthesized beams of the merged data are listed in Table 2.

It should be noted that only the CO(2–1) data have been complemented by short spacing data from the 30 m telescope whereas we did not get these data at 3 mm. Nevertheless, at

3 mm the short-spacings problem is less severe because the interferometer samples larger regions at lower frequencies.

3. Observational results

For both sources we detect bipolar outflows in CO(2–1) and SiO(2–1) (Figs. 2 & 4). While IRAS 19217+1651 is dominated by one extremely energetic outflow, IRAS 20293+3952 exhibits one collimated jet-like outflow and at least three more outflows. Before discussing their implications for massive star formation we present each star-forming region separately.

3.1. IRAS 19217+1651

3.1.1. Millimeter Continuum

Even at the highest spatial resolution of $\sim 1.5''$ the mm continuum emission of IRAS 19217+1651 remains single-peaked and does not split up into multiple sub-sources (Fig. 1). The millimeter continuum fluxes are given in Table 3. Comparing the 1.3 mm flux obtained with the PdBI and the 1.2 mm single-dish fluxes (Beuther et al. 2002b) we estimate that about 80% of the total continuum flux is filtered out by the interferometer. Compact cm continuum emission and 22 GHz H_2O and 6.7 GHz Class II CH_3OH maser emission observed with the VLA and ATCA (Sridharan et al. 2002; Beuther et al. 2002d) peak at the mm continuum source [2]. It has to be taken into account that IRAS19217+1651 is five times further away than IRAS 20293+3952, and thus we cannot resolve as much structure. Nevertheless, the spatial coincidence of mm/cm continuum emission and the two maser species suggests that the region is dominated by one massive evolving protostar at the cluster center.

Assuming optically thin dust emission at mm wavelength, we calculate the mass and peak column density using the 1.3 mm data following the procedure outlined for the single-dish dust continuum data by Beuther et al. (2002b). Recent studies indicate that the dust opacity index β could be lower than the canonical value 2 at the core centers of massive star-forming regions (Goldsmith et al. 1997 and references therein; Beuther et al. 2004b,a; Kumar et al. 2003). Unfortunately, we cannot properly differentiate between the dust and free-free contributions in the mm regime toward IRAS 19217+1615, and thus not derive β explicitly

[2]Beuther et al. (2002d) presented a similar image with the cm source and one H_2O maser feature being $\sim 5''$ offset to the east. Unfortunately, the astrometry in their image was wrong, here we present the correct positions.

for this source. Based on the other studies we set β to 1. We use a dust temperature of 38 K as derived by SED fits to the IRAS data (Sridharan et al. 2002). As discussed by Beuther et al. (2002b), the errors of the estimated masses and column densities are dominated by systematics like the exact knowledge of β or the temperature. For example, reducing β from the canonical value of 2 to 1 lowers the estimated mass by about one order of magnitude. We estimate the masses and column densities to be correct within a factor 5-10. The total gas mass of the central core observed at 1.3 mm with the PdBI is around 220 $M_\odot$, and the peak column density of the order a few times 10^{23} cm^{-2} corresponds to a visual extinction $A_{\rm v} = N_{\rm H}/2 \times 10^{21} \sim 600$ (Table 3).

3.1.2. The molecular outflow

Figure 2 presents the merged PdBI+30m CO(2–1) outflow image obtained for IRAS 19217+1651. We observe a bipolar outflow emanating from the mm core with the main blue emission to the south-west and the main red emission to the north-east. The gas with the highest velocities (± 30 km s^{-1}) is located at the core center, however we find high velocity gas offset from the core as well (see below, Figure 8). The overall collimation of the outflow is pretty high with a collimation degree ~ 3 (length of the outflow divided by its width). The morphology of the blue outflow wing resembles a cone-like structure. The red wing to the north-east shows an elongated feature with a P.A. of 40° with respect to the main outflow axis. The morphology of the red wing is quite different compared with the blue wing, and one can get the impression that in this area might be a second outflow in the north. However, the mass contained in the red wing is very high ($\sim 50\,M_\odot$, Table 4), and it is difficult to imagine such a massive and energetic outflow without a mm continuum source as the counterpart (the 3σ rms of 7.5 mJy corresponds to a mass sensitivity of 4.3 $M_\odot$). Therefore, we conclude that the red and blue wing emission is part of the same outflow emanating from the massive mm core. The different morphologies to the north and south are likely attributed to environmental differences.

The SiO(2–1) emission shown in Figure 2 exhibits a similar outflow morphology as the CO observations but missing the broad lower intensity outflow emission depicted in CO. As SiO is mainly a shock tracer (Schilke et al. 1997) it is likely that SiO is not excited in the outer regions of the outflow. However, it should be mentioned that this difference might also be an observational artifact because we do not have the short spacings data for SiO and thus the larger scale SiO outflow emission could be filtered out by the interferometer. Furthermore, due to the larger primary beam of the PdBI at 3 mm compared to 1 mm (59″ and 22″, respectively) we observe a larger field in SiO and detect an additional bipolar

structure in the west not covered by the CO data. We do not detect a mm continuum source there (the 3 mm continuum covers the same field). Nevertheless, it is likely that a mm continuum source is simply too weak and not detected due to insufficient signal to noise. Adopting the same assumptions outlined in §3.1.1 for the 3 mm continuum data, the 3σ rms of 2.4 mJy corresponds to a mass sensitivity of $\sim 30\,M_\odot$.

3.2. IRAS 20293+3952

3.2.1. Millimeter Continuum

Figure 3 presents the mm continuum data for IRAS 20293+3952 and additionally the cm and H_2O maser emission in that region. Obviously, the overall picture is different from IRAS 19217+1651. We find three mm continuum sources with an H_2O maser associated with the strongest of them. Furthermore, offset from the mm emission there is a resolved cm source indicating a more evolved UCHII region. We do not detect any mm continuum emission at the position of the UCHII region down to the 3σ rms sensitivity limit of 13.5 mJy, corresponding to a mass sensitivity of $0.2\,M_\odot$ assuming optically thin dust emission. Instead of one source dominating the whole region (§3.1.1) IRAS 20293+3952 exhibits four sources possibly interacting with each other. Comparing the interferometric and single-dish fluxes (Beuther et al. 2002c), nearly 90% of the total flux is filtered out in IRAS 20293+3952, even more than in IRAS 19217+1651.

Assuming optically thin dust emission with a dust temperature of 56 K (Sridharan et al. 2002) using again the dust opacity index $\beta = 1$ (§3.1.1) we derive masses and column densities for the three mm clumps. The masses of each clump listed in Table 3 are about two orders of magnitude below the value derived for IRAS 19217+1651 whereas the beam averaged column densities are of the same order, only lower by factors of 2-6.

The clump masses between 1 and $3\,M_\odot$ appear low regarding the overall luminosity of the region of $10^{3.8}\,L_\odot$. However, the luminosity is measured with the large IRAS beam and thus comprises also the nearby UCHII region. Assuming the cm emission to be optically thin, Sridharan et al. (2002) estimated the stellar luminosity of its central source to be close to the infrared-derived value. Therefore, while it is possible that we partly underestimate the mass of the dust cores in IRAS 20293+3952, it seems obvious that the dominant luminosity source is the UCHII region. The mm sources nearby, which trigger all the spectacular outflows, form a kind of secondary cluster of intermediate-mass sources.

3.2.2. Four molecular outflows

As the millimeter continuum, the outflow emission in IRAS 20293+3952 is more complex than in IRAS 19217+1651 as well. The CO velocity spread down to zero intensity with $\Delta v \sim 92\,\mathrm{km\,s^{-1}}$ in IRAS 20293+3952 is also larger compared to $\Delta v \sim 64\,\mathrm{km\,s^{-1}}$ in IRAS 19217+1651. Figure 4 shows three images of the CO red and blue outflow emission (extreme outflow velocities, moderate outflow velocities, and all outflow velocities), it also sketches the four outflows identified in that region. Figure 5 shows the SiO(2–1) emission of the region. As the region is complex not all identifications are unambiguous and some features can belong to one or the other outflow, or even outflows which we do not identify yet. Our outflow identifications are based on the CO and SiO morphology and the assumption that there are no other outflow-powering sources than mm1 to mm3.

Outflow (A): The most prominent feature in Figure 4 is the collimated jet-like outflow emanating from mm1 in south-west–north-eastern direction. Especially interesting is the red wing with its extreme collimation extending about 1 pc in length. The collimation degree of this red wing is ~ 8 as high as known values for the most collimated low-mass outflows (Richer et al. 2000). Figure 6 shows a close-up of moderate and extreme velocities for the red emission stressing that the higher-velocity gas is more collimated than the lower-velocity gas. The ratio of the projected width perpendicular to the outflow direction of the moderate-velocity gas versus the extreme-velocity gas is ≥ 2. This morphology resembles the observations of low-mass outflows (Bachiller 1996). It is unlikely that the moderate-velocity gas is strongly confused by the ambient gas because the chosen velocity interval [13,25] $\mathrm{km\,s^{-1}}$ for the moderate-velocity component is still significantly offset from the velocity of rest $v_{\mathrm{LSR}} = 6.5\,\mathrm{km\,s^{-1}}$. Furthermore, Figure 8 presents a position velocity diagram of outflow (A), and we find high-velocity gas at the outflow center as well as at the very end of the red wing. The morphology of the blue wing is less clear which might be partly due to the smaller extend of the mosaic in that direction (§2). The blue feature highlighted with the dashed arrow in Fig. 4 could be part of a larger cone of the blue wing of (A), but it is also possible that there is another outflow consisting of this blue feature and maybe the northern red feature we so far associate with outflow (D).

Outflow (B): A second outflow emanates from mm1 in south-eastern direction. The blue CO emission is only observed at a distance of $\sim 20''$ but SiO is observed right to mm1. While the blue emission is strong we do not observe red emission to the north. Partly, this should be due to the small extend of the PdBI mosaic in that direction (§2).

Outflow (C): We observe a third small outflow emanating from mm3 in east-west direction.

Outflow (D): The fourth outflow (D) likely emanates from mm2 and is more or less parallel to outflow B. Again, we see strong blue emission toward the south-east but less red emission toward the north-west. As already mentioned in the context of outflow (A), the red feature in the north could also be part of still another outflow emanating from mm1 with the blue counterpart shown in dashed contours.

Shocked H_2 emission: Additionally interesting is a comparison of the outflow data with shocked H_2 emission at 2.12 μm. The near-infrared H_2 data were taken with the Omega Prime camera on the Calar Alto telescope within the observations of a large sample of massive star-forming regions, the basic data reduction is described in a separate paper by Stanke et al. (in prep.). Figure 7 presents an overlay of the H_2 emission with the CO outflow data and the cm source outlining the UCHII region. We can distinguish a few regions of prominent H_2 emission: first, we find H_2 features associated with the blue CO emission of outflows (A) and (B). Furthermore, we clearly identify ring-like H_2 emission around the UCHII region. Judging from the morphology, the red CO outflow (A) bends partly around that ring-like structure. In addition, there are strong H_2 emission knots between mm2 and mm3 which could be associated with outflows (C) and (D), but which may also be part of the ring-like H_2 emission.

4. Discussion

4.1. Molecular outflows

4.1.1. Masses and energetics

The CO(2–1) data allow to estimate the masses and energetics of the different outflows in both sources. However, for IRAS 20293+3952 it is not always clear whether emission belongs to one or the other outflow. For example, the emission right at the center of mm1 can be part of the outflows (A) as well as (B). Most likely, both outflows contribute to the observed emission. Similarly, the emission between mm2 and mm3 could be part of the outflows (C) and (D). In the following calculations these regions of overlap are always attributed to both contributing outflows.

We calculate opacity-corrected H_2 column densities in both outflows following the approach outlined in Beuther et al. (2002c). The average temperature in the outflows is set to 30 K and the average line opacity in the outflow wings to $\tau(^{13}\mathrm{CO}\ 2-1) = 0.1$ (based on observations by Choi et al. 1993). According to Cabrit & Bertout (1990) derived masses

are accurate to a factor 2 to 4, whereas the accuracy of dynamical parameters are lower, at about a factor 10. The derived masses and energetic parameters for the outflows in both sources are presented in Table 4.

A comparison of the outflow mass $M_{\rm out} = 75\,{\rm M}_{\odot}$ in IRAS 19217+1651 with the single-dish observations derived value of $108\,{\rm M}_{\odot}$ (Beuther et al. 2002c) shows that both values agree within 25%. This gives confidence that the merging process of the PdBI data with the single-dish observations worked reasonably well and we recovered most of the outflow emission. Such a comparison is more difficult for IRAS 20293+3952 because the single-dish data did not resolve the multiple outflows.

The values presented in Table 4 confirm that IRAS 19217+1651 powers a very massive and energetic molecular outflow on pc scales. The derived outflow rate $\dot{M}_{\rm out}$ is of the order $10^{-3}\,{\rm M}_{\odot}{\rm yr}^{-1}$. Under the assumption of momentum driven outflows this leads to an estimate of the accretion rate of the order a few times $10^{-4}\,{\rm M}_{\odot}{\rm yr}^{-1}$ (for details on the assumptions see Beuther et al. 2002c). Accretion rates of that order are high enough to overcome the radiation pressure of a forming star and build the most massive stars via accretion processes (e.g., Norberg & Maeder 2000; McKee & Tan 2003).

The outflow parameters for IRAS 20293+3952 are all about one order of magnitude below the values for IRAS 19217+1651. They are higher than typical masses and energetics in the low-mass regime (Richer et al. 2000) but below often observed parameters for massive outflows (Shepherd & Churchwell 1996a; Ridge & Moore 2001; Beuther et al. 2002c; Gibb et al. 2003). The outflows emanate from a cluster of intermediate-mass protostars right in the vicinity of a more evolved UCHII region. The data show that the UCHII region is too evolved to trigger any collimated outflow. Thus, although most of the bolometric luminosity stems from the UCHII region, nearly all the mechanical force $F_{\rm m}$ and mechanical luminosity $L_{\rm m}$ (Table 4) is due to the outflows from the intermediate-mass cluster. Based on the outflow rate $\dot{M}_{\rm out}$ we can again estimate accretion rates between 10^{-5} and $10^{-4}\,{\rm M}_{\odot}{\rm yr}^{-1}$, right between typical values for low- and high-mass star-forming regions.

4.1.2. Dynamical interactions in IRAS 20293+3952

The presence of four molecular outflows emanating from three mm continuum sources, and one UCHII region within less than 1 pc projected on the plane of the sky reveals multiple regions of interaction. Obviously, the CO and SiO emission around the mm sources is caused by different interacting molecular outflows, but the UCHII seems to affect the outflows as well. Assuming that the ring-like shocked H_2 emission is caused by the star powering the

central UCHII region, its sphere of influence extends as far as outflow (A) and the mm sources mm2 and mm3. The H_2 emission between mm2 and mm3 might thus not be just due to the outflows (C) and (D) but there may also be contributions from the UCHII region. With the data so far, we cannot unambiguously conclude whether the spatial association of mm2 and mm3 with the H_2 ring is simple coincidence or whether the formation of mm2 and mm3 might even be associated with some triggering mechanism from the UCHII region.

Even more intriguing is the spatial bending of the red wing of outflow (A) right north of the UCHII region. Figure 7 shows that this bending follows largely the ring-like H_2 feature in that region. This could be just due to projection effects, but it is also possible that an expanding pressure wave from the UCHII region intercepts with outflow (A) and pushes its gas slightly to the north. The radius of the H_2 shell is about $7.7''$ corresponding to 15000 AU at a distance of 2 kpc.

4.2. Position-velocity diagrams of massive outflows

Position-velocity (p-v) diagrams are often used as a tool to understand the driving mechanisms of outflows (e.g., Smith et al. 1997; Downes & Ray 1999; Lee et al. 2001, 2002). In addition to p-v diagrams of outflows presented in this paper, Figure 8 shows p-v diagrams of two other massive outflow sources taken from the same initial source sample: IRAS 23033+5951 observed in CO(1–0) with BIMA by Wyrowski et al. (in prep.) and IRAS 20126+4104 observed in CO(2–1) with the IRAM 30 m by Lebron et al. (in prep.). For details on the outflow characteristics, we refer to the corresponding papers, here we are only interested in their p-v diagrams.

The range of outflow masses for these four outflows is broad, from intermediate masses in IRAS 20293 to very high masses in IRAS 23033 ($M_{\rm out} = 119\,{\rm M}_\odot$, Wyrowski et al., in prep.). The bolometric luminosities also vary by orders of magnitude: outflow (A) in IRAS 20293 is driven by an intermediate-mass protostar, and the bolometric luminosities of IRAS 20126, IRAS 23033 and IRAS 19217 are $10^{3.9}$, $10^{4.0}$ and $10^{4.9}\,{\rm L}_\odot$, respectively. Admittedly, the statistical number of presented outflows is low, but nevertheless we cover a broad range of luminosities and masses and can compare these data with theories and previous studies in the low-mass regime.

We observe mainly two features in the p-v space: first of all, high-velocity gas is detected at the outflow centers in IRAS 19217 and IRAS 20293. There is some high-velocity gas in IRAS 23033 near the center as well, but the red and blue is shifted spatially to the other side of the outflow center compared with the larger scale flow, thus this high-velocity gas

might be due to a second outflow spatially just barely resolved (Wyrowski et al., in prep.). IRAS 20126 does not show any high-velocity gas near the outflow center. Secondly, we observe high-velocity gas at some distances from the core center: IRAS 23033 exhibits the so-called Hubble-law in the blue wing, i.e., a velocity increase with distance from the core center. In IRAS 20293, the velocity also increases gradually with distance in the red wing, and the emission feature at the very end of the collimated outflow shows emission at all velocities again. In IRAS 20126, we see a gradual velocity increase and then decrease again with distance from the core center, this is the only source where the p-v diagram is rather symmetric. IRAS 19217 shows some high-velocity features at distances from the center as well, but there is no real symmetry with respect to the core center.

We compare our data with high-spatial-resolution observations of low-mass outflows by Lee et al. (2000, 2002). They observed 10 low-mass sources and found mainly two kinematic features in the p-v diagrams: parabolic structures originating at the driving source and convex spur structures with high-velocity gas near H_2 bow shocks. While the parabolic structures can be explained by wind-driven models the spur structures are attributed to jet-driven bow-shock models (Lee et al. 2000, 2001, 2002). While some outflows show clear signatures of one or the other model, there are also a few sources which exhibit signatures of both. Lee et al. (2002) propose that a combination of a jet- and wind-driven model might explain all features in a more consistent way. In their first published sample, they see nearly no central high-velocity gas (Lee et al. 2000), whereas in later published sources some central high-velocity gas is observable (Lee et al. 2002). High-velocity features at the core centers are likely due to jets but they can also be mimicked by highly inclined winds (Fig. 10, Lee et al. 2001).

Transferring the low-mass and simulation results to our data, we find clear spur and Hubble-law jet-signatures in IRAS 20293 and IRAS 23033, whereas IRAS 20126 can be explained by a wind-driven model (e.g., compare with RNO 91, Fig. 10, in Lee et al. 2000). IRAS 19217 is a less clear-cut case because we find the jet-indicating high-velocity gas at the core center but also features further outside which resemble more the parabolic structures indicative of wind-driven models. Morphologically, the IRAS 19217 outflow is also somewhat intermediate between a collimate jet-like outflow and cavity-like features indicative rather of a wind (Figure 2). Likely, both mechanisms contribute to the observed outflow in IRAS 19217.

To summarize, our intermediate- to high-mass outflow data show kinematic signatures which can be explained by jet- and/or wind-driven models. We do not find any striking difference to low-mass position-velocity diagrams. Similar to their low-mass counterparts, no single model is yet capable to explain all observations consistently.

5. Conclusions

The presented analysis of high-spatial-resolution observations of intermediate- to high-mass molecular outflows indicates that the outflow morphologies/kinematics and thus their driving mechanisms do not vary significantly compared to their low-mass counterparts. The higher the source luminosity the more energetic the outflows, but the qualitative signatures are similar. These observations indicate that similar driving mechanisms can be responsible for outflows of all masses.

We find an extremely collimated jet-like outflow emanating from the intermediate-mass source mm1 in IRAS 20293+3952. This outflow shows the highest degree of collimation at highest velocities and slightly lower collimation at lower velocities, similar to low-mass sources (Bachiller 1996). The whole region IRAS 20293+3952 shows many signs of dynamical interactions, not only between the different outflows (at least four) but there are also indications of a shock wave from the nearby UCHII region interacting with the collimated outflow. While the UCHII region is the main source of luminosity in IRAS 20293, most of the mechanical force stems from the outflows of the intermediate-mass sources.

The high-mass source IRAS 19217+1651 shows a nice bipolar outflow, slightly less collimated than the outflow (A) in IRAS 20293, but still comparable to many low-mass flows. This region is strongly dominated by the central core which exhibits mm/cm continuum emission as well as H_2O and CH_3OH maser emission.

Position-velocity diagrams of molecular outflows from intermediate to high masses show similar signatures as known for low-mass outflows. Some sources are better explained by jet-driven outflows whereas others seem to be due rather to wind-driven outflows. IRAS 19217 exhibits signatures of both. The proposal from Lee et al. (2002) that a combination of both driving mechanisms can explain all outflows consistently also holds for our sample.

Estimated accretion rates are of the order a few times $10^{-5}\,M_{\odot}yr^{-1}$ for the intermediate-mass sources in IRAS 20293 and a few times $10^{-5}\,M_{\odot}yr^{-1}$ for the high-mass source IRAS 19217, consistent with models forming stars of all masses via accretion (e.g, Norberg & Maeder 2000; McKee & Tan 2003).

The data presented in this paper further support the idea that massive stars form via similar accretion-based processes as their low-mass counterparts. The main difference appears to be their clustered mode of formation and increasing accretion rates and energetics with increasing stellar mass and luminosity. However, investigations of the most massive stars is just beginning, and studies like this one so far rarely exceeded sources with luminosities $> 10^5\,L_{\odot}$. This is to a large degree due to the fact that there simply do not exist many sources with far higher luminosity which are in a state of evolution prior or at the very beginning to

form a significant UCHII region. Therefore, on the one hand we have to extend massive star formation research significantly to even higher luminosities to confirm the present results or to identify possible differences in that regime. On the other hand, the constrains set on the massive star-forming processes are yet mostly indirect, e.g., observing molecular outflows on large scales and inferring the processes likely taking place at the cluster centers. As the spatial resolution and sensitivity of (sub-)mm interferometers increase steadily, it is now necessary to really study the cluster centers and try to resolve the relevant processes in more direct ways. For example, massive disk which are crucial to explain the observed outflows need to be properly identified, resolved and studied to manifest its physical conditions. Furthermore, the strong radiation of the massive protostars significantly changes the chemistry of those central regions. The broad bandwidth and high spatial resolution of current and future (sub-)mm interferometers (SMA, PdBI, CARMA, and further on ALMA) will shed light on many such processes.

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Table 1. Source characteristics

Source	R.A. J2000	Dec. J2000	$v_{\rm LSR}$ km s^{-1}	D kpc	L L$_\odot$	M M$_\odot$	$M_{\rm out}$ M$_\odot$	$E_{\rm out}$ erg
19217+1632	19:23:58.78	16:57:36.52	3.5	10.5	$10^{4.9}$	9500	108	$3.6\,10^{47}$
20293+3952	20:31:10.70	40:03:09.98	6.3	2.0	$10^{3.8}$	460	9	$7.8\,10^{46}$

Note. — The source parameters are taken from Sridharan et al. (2002); Beuther et al. (2002b,c): the velocity of rest $v_{\rm LSR}$, the distance D, the luminosity L, the core mass M, the outflow mass $M_{\rm out}$ and the outflow energy $E_{\rm out}$

Table 2. Synthesized beams

Source	Wavel. mm	Obs	Beam $''$(P.A.)	lin. res. AU
19217+1632	1.3 cont	PdBI	1.58×1.43 (32°)	$\sim 16600 \times 15000$
19217+1632	1.3 line	PdBI+30m	1.93×1.69 (51°)	$\sim 20300 \times 17700$
19217+1632	3 cont	PdBI	4.93×3.78 (58°)	$\sim 51800 \times 39700$
19217+1632	3 line	PdBI	6.05×4.91 (71°)	$\sim 63500 \times 51600$
20293+3952	1.3 cont	PdBI	1.91×1.75 (−101°)	$\sim 3800 \times 3500$
20293+3952	1.3 line	PdBI+30m	1.96×1.79 (84°)	$\sim 3900 \times 3600$
20293+3952	3 cont	PdBI	5.10×4.31 (50°)	$\sim 10200 \times 8600$
20293+3952	3 line	PdBI	5.10×4.36 (49°)	$\sim 10200 \times 8700$

Table 3. Millimeter continuum data

Source	#	$S_{\rm peak}^{\rm 3mm}$ $\frac{\rm mJy}{\rm beam}$	$S_{\rm int}^{\rm 3mm}$ mJy	$S_{\rm peak}^{\rm 1mm}$ $\frac{\rm mJy}{\rm beam}$	$S_{\rm int}^{\rm 1mm}$ mJy	M $M_\odot$	N cm^{-2}
19217+1632		56	68	100	379	216	$6\,10^{23}$
20293+3952	1	13	19	95	201	3	$2\,10^{23}$
20293+3952	2	7[a]	12[a]	47	92	1	$1\,10^{23}$
20293+3952	3	–	–	37	76	1	$1\,10^{23}$

[a]Sources mm2 and mm3 are unresolved at 3 mm.

Table 4. Outflow parameter

source	$M_{\rm blue}$ $M_\odot$	$M_{\rm red}$ $M_\odot$	$M_{\rm out}$ $M_\odot$	p $\frac{M_\odot {\rm km}}{\rm s}$	E 10^{46}erg	size pc	$t_{\rm dyn}$ yr	$\dot{M}_{\rm out}$ $\frac{M_\odot}{\rm yr}$	$F_{\rm m}$ $\frac{M_\odot {\rm km}}{\rm s\ yr}$	$L_{\rm m}$ $L_\odot$
19217+1652	24.4	50.4	74.8	2210	68	1.6	48200	1.5e-3	4.6e-2	116
20293+3952(A)	1.3	0.7	2.0	90	4.1	0.20	4300	4.5e-4	2.1e-2	79
20293+3952(B)	1.0	0.0	1.0	46	2.1	0.17	3700	2.7e-4	1.2e-2	46
20293+3952(C)	0.2	0.1	0.3	9	0.2	0.06	2100	1.5e-4	4.1e-3	9
20293+3952(D)	0.8	0.1	0.9	22	0.6	0.31	12600	6.8e-5	1.7e-3	4

Note. — The listed parameters are the outflow masses in the blue wing $M_{\rm blue}$, the red wing $M_{\rm red}$ and the total mass $M_{\rm out}$, the momentum p, the energy E, the size of the flows, their dynamical timescale $t_{\rm dyn}$, the outflow rate $\dot{M}_{\rm out}$ and their mechanical forces $F_{\rm m}$ and luminosities $L_{\rm m}$.

Fig. 1.— Continuum emission in IRAS 19217+1651: the grey-scale presents the 3 mm and the thin contours the 1.3 mm continuum. The thick contours show the 3.6 cm continuum emission. The symbols point at the maser as labeled in the top right. The large and small beams at the bottom right are from the 3 mm and 1.3 mm observations, respectively. The mm data are contoured from 20 to 90% (10% steps) from the peak emission (Table 3). The cm observations are contoured from 30 to 90% (10% steps) from the peak emission of 19.6 mJy/beam.

Fig. 2.— CO(2–1) (left panel) and SiO(2–1) (right panel) observations of IRAS 19217+1632: The grey scale with thick contours presents the 1.3 mm continuum emission contoured from 15 to 95% (10% steps) from the peak emission (Table 3). Full and dotted contours show the red and blue shifted emission in both species, respectively. The velocity ranges for the CO(2–1) data are: blue v=[-35,-3] $\mathrm{km\,s^{-1}}$ and red v=[9,29] $\mathrm{km\,s^{-1}}$. For SiO(2–1) the velocity ranges are: blue v=[-12,-1] $\mathrm{km\,s^{-1}}$ and red v=[6,15] $\mathrm{km\,s^{-1}}$. The CO and SiO beams are shown at the bottom left of each panel, respectively. Contour levels of the line emission are always from 10 to 90% (10% steps) from the peak intensities ($S_{\rm peak\_blue}(\mathrm{CO}(2-1)) =$ 50.8 Jy/beam, $S_{\rm peak\_red}(\mathrm{CO}(2-1)) =$ 39.1 Jy/beam, $S_{\rm peak\_blue}(\mathrm{SiO}(2-1)) =$ 1.3 Jy/beam, $S_{\rm peak\_red}(\mathrm{SiO}(2-1)) =$ 1.1 Jy/beam). The line in the left panel sketches the axis of the p-v diagram presented in Figure 8.

Fig. 3.— Continuum emission in IRAS 20293+3952: the different features are marked at the top right of each panel. At the bottom left, we present the 1.3 mm and 3 mm beams, respectively. The mm data are contoured from 10 to 90% (10% steps) from the peak emission (Table 3). The cm observations are contoured from 40 to 90% (10% steps) from the peak emission of 0.8 mJy/beam.

Fig. 4.— CO(2–1) emission in 20293+3952 (PdBI+PV): the full and dotted/grey scale contours show the red- and blue-shifted emission, respectively. The velocity ranges are: (a) blue [-40,-11] kms, red [25,52] km s^{-1}; (b) blue [-10,0] km s^{-1}, red [13,25] km s^{-1}; (c) blue [-40,0] kms, red [13,52] km s^{-1}. The 1.3 mm beam is shown at the bottom right of each panel, the three stars and the square mark the positions of the mm sources and the UCHII region, respectively. The arrows and letters sketch the four outflows discussed in the main body. Contour levels are always from 10 to 90% (10% steps) from the peak intensities ($S_{\rm peak\_blue\_ext}$(CO(2 − 1)) = 10.0 Jy/beam, $S_{\rm peak\_red\_ext}$(CO(2 − 1)) = 19.9 Jy/beam, $S_{\rm peak\_blue\_mod}$(CO(2 − 1)) = 29.7 Jy/beam, $S_{\rm peak\_red\_mod}$(CO(2−1)) = 13.0 Jy/beam, $S_{\rm peak\_blue\_all}$(CO(2−1)) = 34.5 Jy/beam, $S_{\rm peak\_red\_all}$(CO(2−1)) = 33.8 Jy/beam).

Fig. 5.— SiO(2–1) in IRAS 20293+3952: the full and dotted contours show the red- and blue-shifted emission, respectively. The 3 mm SiO beam is presented at the bottom left, the three stars and the square mark the positions of the mm sources and the UCHII region, respectively. The arrows and letters sketch the four outflows discussed in the main body. Contour levels are always from 5 to 95% (10% steps) from the peak intensities ($S_{\rm peak\_blue}$(SiO(2 − 1)) = 2.5 Jy/beam, $S_{\rm peak\_red}$(SiO(2 − 1)) = 4.9 Jy/beam).

Fig. 6.— Red CO(2–1) emission in IRAS 20293+3952: the grey-scale shows the moderate velocities ([13,25] km s^{-1}) and the contours present the high-velocity gas ([25,52] km s^{-1}). The 1.3 mm beam is shown at the bottom left, the three stars and the square mark the positions of the mm sources and the UCHII region, respectively. Contour levels are always from 10 to 90% (10% steps) from the peak intensities as presented in Fig. 4.

Fig. 7.— The grey-scale presents the H_2 emission (Stanke et al., in prep.). The thick and thin black contours outline the red and blue CO emission, respectively. The white contours present the 3.6 cm VLA observations of the UCHII region, and the three stars mark the positions of the mm sources. The contouring is the same as in the previous images.

Fig. 8.— Position-velocity diagrams of the outflows in IRAS 19217+1632 and IRAS 20293+3952 (outflow A) presented in this paper. Furthermore we show two position-velocity diagrams taken from the literature: IRAS 23033+5951 (observed with BIMA, Wyrowski et al., in prep.) and IRAS 20126+4104 (observed with the IRAM 30 m, Lebron et al., in prep.). The horizontal lines mark the centers of the outflows which always correspond to the main mm continuum sources. Resolution elements are shown at the bottom left of each panel.

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